

## Development of a Prototype Borehole Profilometer to Estimate Roof-Bolt Anchorage Capacity from Borehole Roughness Measurements— Laboratory Tests

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### ABSTRACT

Researchers at the National Institute for Occupational Safety and Health's (NIOSH) Spokane Research Laboratory are developing a borehole profilometer to dynamically measure the roughness profile of boreholes used to install roof bolts fully encapsulated with resin. Numerical measures of roughness were calculated from profiles of borehole surface roughness to determine potential roof bolt anchorage capacity. The concept of dynamically profiling was proven through the following series of laboratory tests: a sensitivity test using various grits of sandpaper, a known-profile test along a section of a concrete hole, and a simulated borehole test in a pipe with machined grooves. Two profilometer prototypes were developed that measure slight changes in the radius of a borehole using either strain-gauged, spring-steel arms or rigid, steel arms attached to a spring-loaded cone and a linear potentiometer. Both instruments performed reasonably well in the laboratory and were subsequently tested in boreholes drilled in two concrete blocks using different drilling techniques to obtain three different borehole surface roughnesses. A Z2 roughness parameter was calculated with data from the first profilometer, and an average radial increment was calculated from the test results of the second profilometer. Although both instruments were able to readily distinguish the difference between smooth and rough boreholes, the correlation coefficient ( $r^2$ ) for a linear relationship between Z2 and average radial increment was 0.577. Pull tests were conducted with resin bolts installed in the concrete blocks, but maximum pull-out strength could not be correlated to borehole roughness because in each of these tests, failure occurred at the resin-bolt interface. A more sophisticated prototype has been designed to measure surface roughness and also accurately determine the location and tilt of the instrument in the borehole. However, this instrument has not yet been fabricated or tested.

### INTRODUCTION

Each year, approximately 100 million roof bolts are installed in mining, tunneling, and construction projects throughout the United States (1). About 80% of these bolts use polyester resin as a means of anchorage. Because resin-grouted rebar bolts are one of the primary means of rock support in U.S. mines, much research has been conducted to investigate and document their ground support characteristics. Pettibone conducted many baseline tests that demonstrated best procedures and practices for obtaining sufficient

anchorage with three resins, which were commercially available in January 1983 (2). Serbousek and Signer installed 48 instrumented bolts in concrete blocks and found that the average anchorage length for transfer of load through the grout to the host medium was 56 cm (22 in) (3). Tadolini later found that a reduced annulus of resin can shorten the load-transfer length to 30.5 cm (12 in) (4). In weak ground, fully-grouted bolts are prone to fail at the resin-rock interface (5, 6). As a result of this problem, reducing ground fall hazards in coal mines with low-strength roof has been identified as one of NIOSH's research priorities. The load capacity of the bolt and proper roof bolt design are critical factors in successfully supporting the mine roof (7, 8). Consequently, achieving sufficient borehole anchorage capacity is an important element of roof control.

From 1998 to 2002, 61 underground miners were fatally injured by fall of ground, accounting for 43% of all the underground mining fatalities during that five-year period (9). Over the same years, lost-time injuries from fall of ground were 1.25 per 100 workers, ranking second only to the materials handling rate of 2.59. In their study of accidents and fatalities, Biswas and Zipf (10) found that from 1984 to 1999, 15.52% of ground-fall accidents were initiated by roof support failure. Assuming a similar trend over the five-year period from 1998 to 2002, roof-support failure may have caused 9 or 10 fatalities, (about 2 fatalities per year) and approximately 0.19 lost-time accidents per 100 workers. Although the percentage of roof-support-failure accidents caused by insufficient bolt anchorage has not been clearly documented, finding a practical solution to insufficient roof bolt anchorage could potentially prevent a significant number of accidents, both fatal and nonfatal.

Using instrumented roof bolts (11, 12), rock strain strips (ROSS) and miniature data acquisition systems (MIDAS), Signer and Sunderman (13) demonstrated that strain in the roof bolt is significantly smaller than strain in the roof rock, suggesting that mechanical interlock between the resin and the rock provides anchorage instead of chemical bond. Giraldo et al. (14) demonstrated that roof-bolt anchorage capacity in weak rock could be improved by conditioning the surface of the borehole. In this case, surface conditioning was achieved by cutting a helical groove in the borehole wall with either a Helical Drag Bit (HDB) or with Helical Roof Bolt (HRB). Consequently, the surface roughness of the borehole appears to be a critical factor in achieving sufficient roof bolt anchorage. In weak rock, surface roughness is even more important because larger asperities in the surface fabric are required to

## 26th International Conference on Ground Control in Mining

achieve the same degree of roof-bolt anchorage obtained in stronger rock. Further research was needed to develop a scientific method for measuring borehole surface roughness and relating this important factor to roof-bolt anchorage capacity. For this reason, NIOSH researchers commenced work to develop both an instrument and an experimental method whereby some measure of borehole surface roughness can be related to roof-bolt anchorage capacity.

At present, the short encapsulation pull test (SEPT) (15,16) is the standard method used to measure the anchorage capacity of fully-encapsulated resin roof bolts. However, these tests are cumbersome and can only be conducted periodically without disrupting production crews. A more efficient method or tool is needed so that the anchorage capacity of roof bolts can be quickly assessed during the mining cycle, particularly as roof conditions change.

In this paper, a prototype average borehole radius profilometer is described that can be used to quickly measure the roughness of a borehole and thus estimate its roof-bolt anchorage capacity. The evolution of the prototype's design to date is explained, a proof of concept for dynamically profiling the roughness of a borehole is demonstrated, and experiments to correlate roughness indicators and SEPTs in two different media are described. The aim of this research is to develop a means of quickly estimating a borehole's anchorage capacity and, thereby, determining whether hole conditioning is needed.

### APPROACH

In selecting a method to estimate the anchorage capacity of a borehole, several different instruments were developed and tested, as explained in further detail in the next section of this paper. As each instrument prototype was developed, simple tests were performed with the instrument to examine whether that particular method would work. Once a prototype instrument had successfully shown promise in these simple tests, it was to be tested in boreholes drilled in two 0.6 m × 0.6 m × 1.8 m (2 ft × 2 ft × 6 ft) concrete blocks so that roughness measurements could be correlated with maximum load measurements from SEPTs conducted in those same boreholes.

The first block was cast with a prestress batch of concrete mix (i.e., a high-strength mix designed for use in concrete structures that are prestressed with bolts or cables prior to their installation), and the second block was cast with a common batch of concrete mix (hereafter referred to as the regular block). Three different sets of 3-1/2-cm- (1-3/8-in-) diameter holes were drilled in each block (figure 1) to depths ranging from 35 to 46 cm (14 to 18 in). Three significantly different borehole surface roughnesses were obtained using the following drill bits (figure 2) and drilling equipment:

- a diamond bit with a rotary drill,
- a star bit with a small jackleg drill, and
- a tungsten-carbide "dusthog" bit with a roof bolting machine.

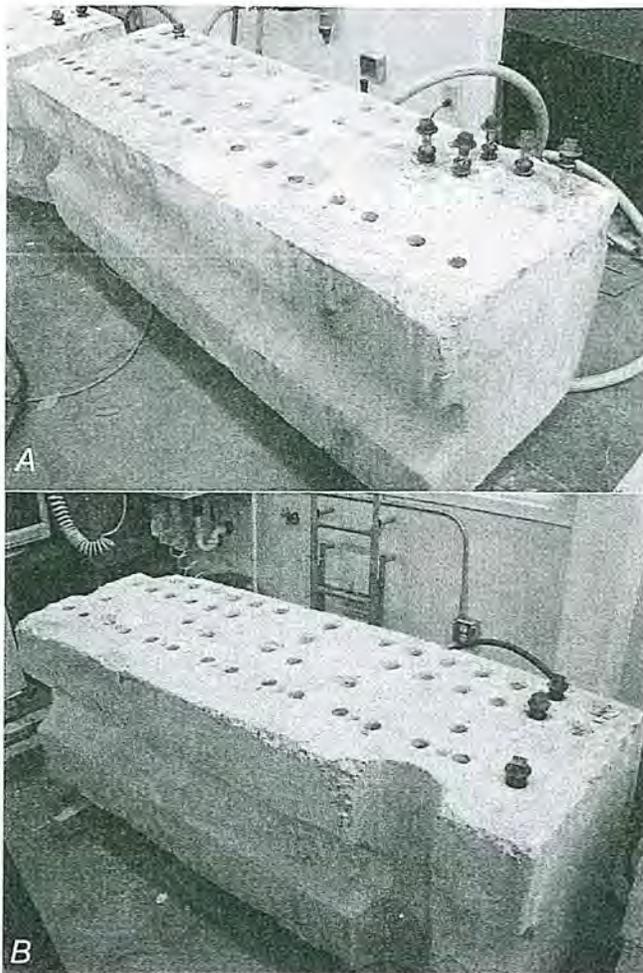


Figure 1. Concrete blocks and boreholes used to evaluate prototype profilometers. A, Prestress-mix block; B, regular-mix block.

Cores, approximately 3.00 cm (1.18 in) in diameter, were recovered from the diamond-drilled holes and tested to determine uniaxial compressive strength, modulus of elasticity, and Poisson's ratio (Table 1). During an elastic properties test, a specimen was incrementally loaded to a level much less than its yield point to ensure that the specimen's behavior remained within the elastic range of its stress-strain response. The test results for uniaxial compressive strength appear to be reasonable for both the prestress mix and the regular mix; the coefficient of variation ranges from 7.25% to 11.72%. However, results for modulus of elasticity and Poisson's ratio varied much more widely. Possible explanations are that the maximum size of the aggregate sometimes exceeded 2.5 cm (1 in); the strain gauges were 1.27 cm (0.500 in) in length, which is relatively small in comparison to the size of the aggregate; the stiffness

Table 1.—Strength and elastic properties of concrete blocks (standard deviation values listed after the mean value after "±")

Concrete block	Number of samples	Uniaxial compressive strength		Number of samples	Modulus of elasticity		Number of samples	Poisson's ratio
		MPa	Psi		GPa	Million psi		
Prestress-mix . .	15	58.72 ± 6.88	8,516 ± 998	4	30.3 ± 3.05	4.39 ± 0.442	4	0.195 ± 0.107
Regular-mix . .	8	26.72 ± 1.94	3,875 ± 281	4	25.2 ± 14.1	3.65 ± 2.05	4	0.224 ± 0.199

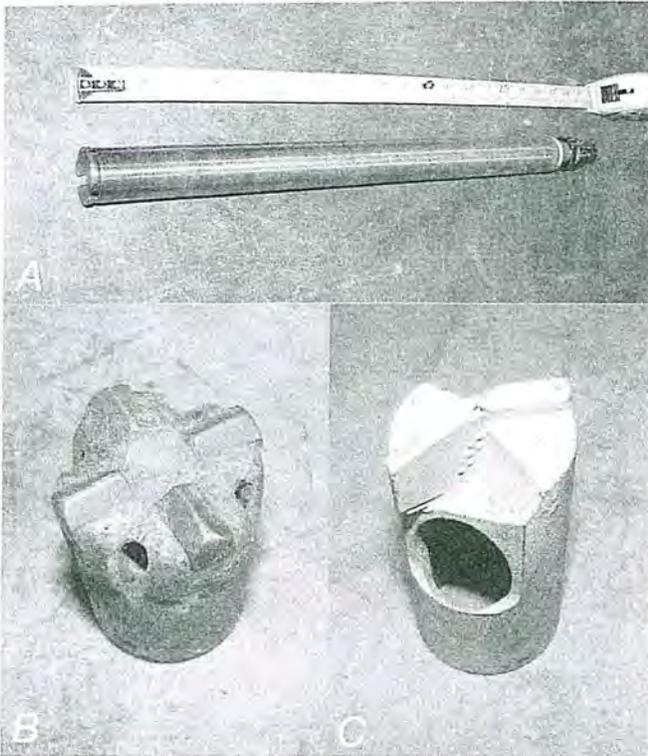


Figure 2. Bits used to drill holes in concrete blocks. *A*, Diamond bit and core barrel used with rotary drill; *B*, star bit used with small, jackleg drill; *C*, tungsten-carbide bit used with roof bolter.

of aggregate and matrix material was variable; and only a small number of samples were available for testing.

#### INSTRUMENT DEVELOPMENT

In the quest to develop and test an instrument that would indicate borehole anchorage, several instrument versions were tried and tested. In the first attempt at instrument development, the jet end of a Drain King bladder was tapped, plugged, and attached to an air supply with a feedback air pressure regulator and digital pressure valve (figure 3). The bladder was inflated against the inside of a pipe that was used to simulate a borehole. While maintaining a constant air pressure, the force required to pull the bladder out of the pipe was measured. Although the air pressure was regulated to the nearest 0.07 kPa (0.01 psi), the bladder was extremely sensitive to any slight change in air pressure, did not expand uniformly, and could easily be over pressurized and herniate.

The next instrument was similar in principle. In this case, three curved platens were forced against the borehole wall with a screw-and-scissor mechanism (figure 4). The screw was turned with a rod that came out of the borehole through the interior of a small installation pipe. After applying a constant torque of 45 cm-N (4 in-lb) with a small torque wrench, the apparatus was pulled with gradually increasing force until the device started to slip. The maximum applied force was measured with a calibrated spring scale. The device was tested in boreholes drilled in concrete and quartzite blocks, but the results were very inconsistent. Maximum pull-out forces were highly dependent on the tilt or orientation of the instrument in the borehole and whether the installation pipe was kept aligned with the centerline of the borehole. More complica-

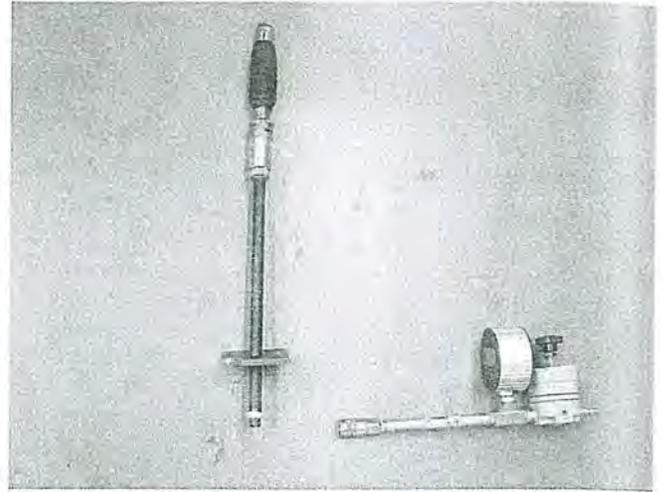


Figure 3. Drain King bladder modified to be a prototype anchorage tester. Pressure gauge and feedback pressure regulator are pictured at right.

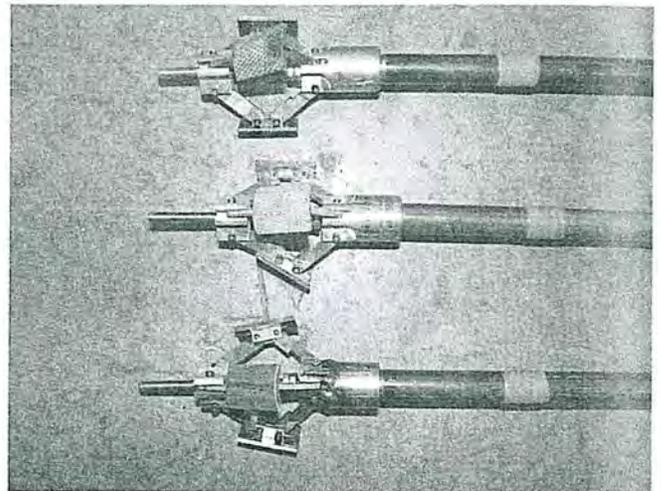


Figure 4. Curved platen anchorage tester. Top, coarse-knurled surface; Middle, medium-knurled surface; Bottom, smooth surface (not knurled).

tions were foreseen with adding centering devices; therefore, additional development of this device was abandoned.

The next generation of instruments was based on the idea of dynamically profiling the roughness of a borehole and developing a relationship between measured roughness and anchorage strength. The first prototype of this instrument was made by modifying the parts of a brake-cylinder hone. The three springs and stem were retrieved from the brake hone, a strain gauge was bonded to the inside surface of each spring, and the stem was mounted to an installation rod. Two prototype instruments were developed which used two different means of contacting the borehole wall (figure 5). In the wheel profilometer, a small 0.953-cm-(0.375-in-) diameter wheel was attached to the end of each spring arm, whereas the stylus profilometer had a 4.00-mm-(0.156-in-) diameter steel ball mounted to the end of each spring arm. Both instruments were designed to operate in a 3-1/2-cm- (1-3/8-in-) diameter borehole. To profile the hole consistently and take readings at even intervals of distance, a device was fabricated so that the instrument could be extracted from the borehole at a constant velocity, using a battery-operated hand-drill (figure 6). The device was positioned at the

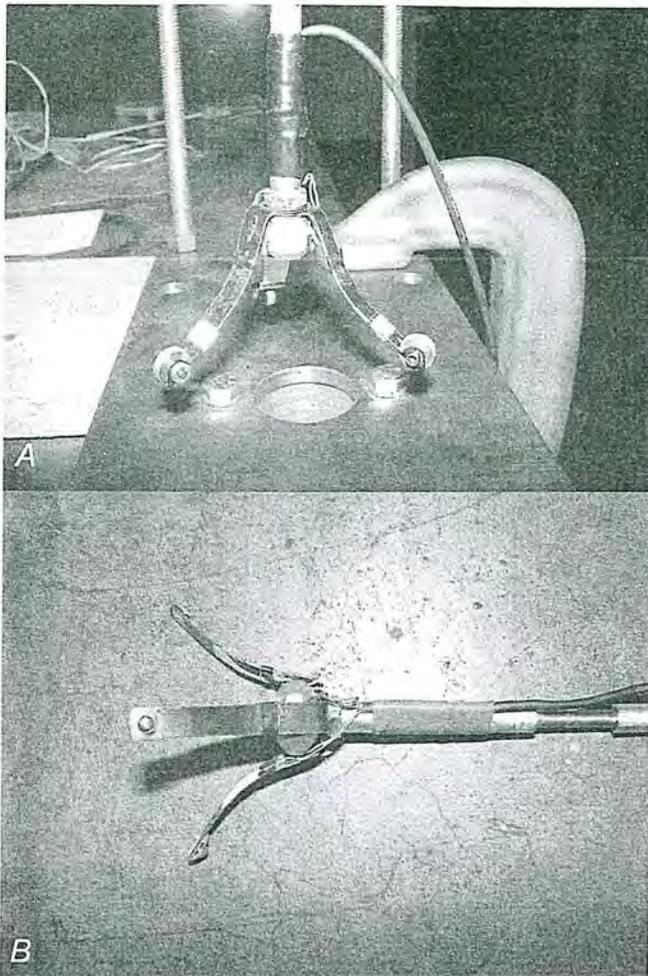


Figure 5. Prototype profilometers made from brake-hone springs and stem. *A*, With wheels for contacts; *B*, with ball bearings for contacts.

borehole collar so that the axis of the threaded extraction rod was visually aligned with the axis of the borehole. The base plate of the device was then securely clamped to the concrete block. As the instrument was extracted from the borehole at a constant speed of approximately 1.9 cm/sec (0.75 in/sec), three strain-gauge sensors were monitored 2,000 times/sec, providing readings approximately every 0.00953 mm (0.000375 in). Although the signal from each sensor indicated significant vibration (or displacement around the centerline of the hole), the average of all three sensor readings significantly dampened this measured vibration and, thus, more closely tracked the radial profile of the borehole. Later, a stabilizer (figure 7) was added to the stem of the instrument to help center it in the borehole and limit the amplitude of this mechanically-induced vibration. The bonds between the strain-gauge solder tabs and the spring-steel arms periodically broke after repeated flexure of the springs. However, this problem was alleviated after switching to smaller, more flexible, lead wires (33-gauge wire instead of 22-gauge wire).

Although the constant-velocity extraction device worked satisfactorily in the laboratory, it was too cumbersome and problematic for use in typical underground mining conditions. To overcome these problems, a more practical, easier to use instrument was designed that could be quickly moved in and out of the borehole by hand. This instrument consists of a spring-loaded cone that forces the forward end of three levers, each attached to a small wheel, against

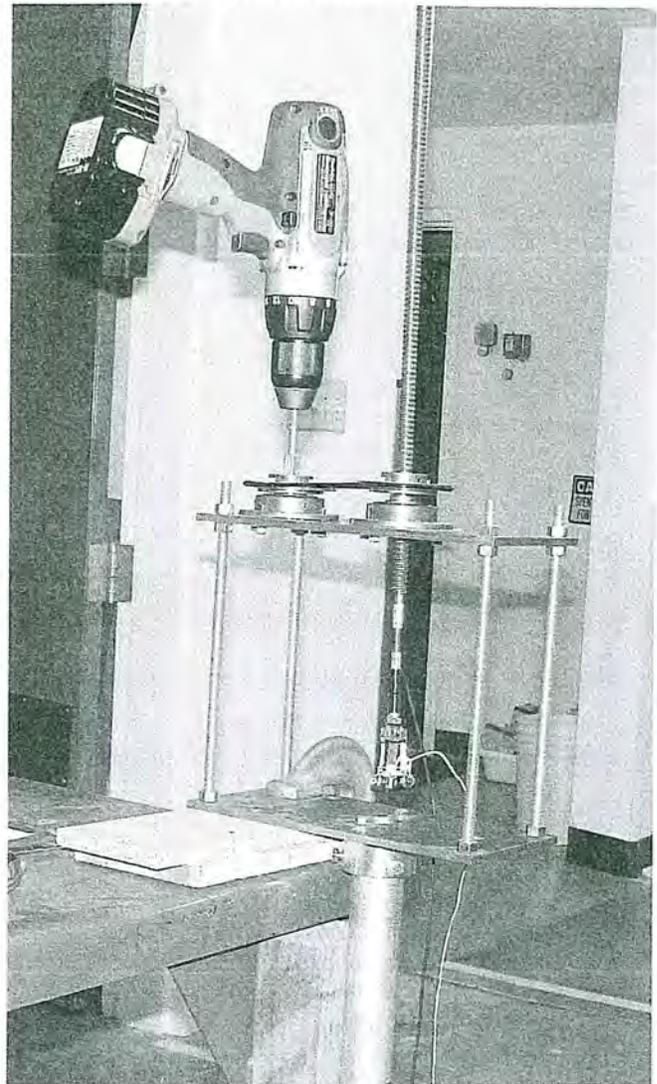


Figure 6. Constant-velocity driver for prototype profilometer.

the borehole wall. The aft end of each lever is also attached to a small wheel which contacts the interior surface of the cone (figure 8). As the diameter of the borehole changes, the position of the forward wheeled lever arms change, causing the aft end wheels to ride along the interior surface of the cone, thus shifting the spring-loaded cone along the axis of the instrument. This change in position or displacement of the spring-loaded cone is, in turn, measured by a single, linear potentiometer. In other words, changes in the radius of the borehole are transferred through the three individual lever arms and mechanically averaged to produce a single displacement measurement along the axis of the borehole. By calibrating the instrument in holes of known radius, this linear displacement can, in turn, be related to an average change in borehole radius. Because the instrument is manually extracted from the borehole, the operator must try to maintain a constant pull velocity by hand if the borehole radius measurements are to be related to specific locations along the borehole. The problem of maintaining a constant pull velocity by hand originally led to the development of a constant-velocity driver for the wheeled brake-hone profilometer. Consequently, the readings collected from the instrument will probably not be uniformly distributed along the length of the borehole. Another disadvantage is that the linear potentiometer typically has less resolution than a strain-gauged spring arm. The current version of this instrument and its data acquisition system are



Figure 7. Prototype profilometer with borehole stabilizer.

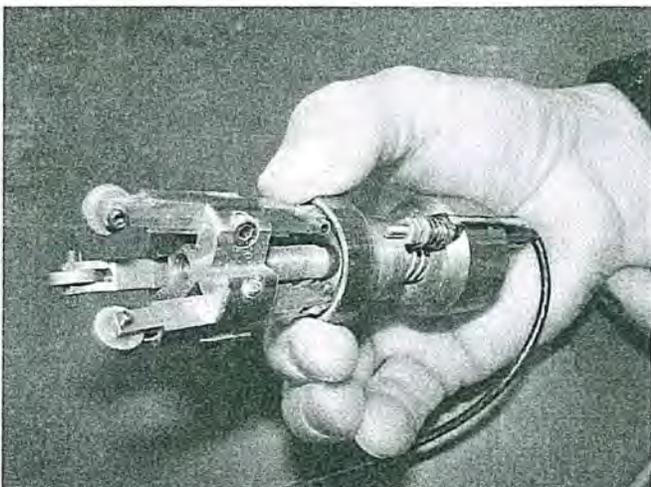


Figure 8. Prototype profilometer with spring-loaded cone that forces levers with wheels against borehole wall. Sensor is a linear potentiometer.

set up to take readings every 0.01 sec, but this sampling interval can be reduced if desired. A modified version can be used in 2.54-cm- (1-in-) diameter boreholes.

A final prototype instrument has been designed, but not yet fabricated or tested. This prototype will have three sensor springs and six stiffer centering springs with wheels. Custom dual-axis tilt meters based upon micro-machined MEMS accelerometers (figure 9) will be incorporated into the sensor frame. A 1.27-cm- (0.500-in-) long cylinder with a 0.95-cm- (0.375-in-) diameter will contain the accelerometer and signal processing components. An optical encoder mounted outside of the borehole will have a cable tether connection to the instrument which will provide an accurate measurement of the depth of the sensor in the hole. Consequently, this prototype will be especially useful for profiling holes with nonlinear centerlines caused by deviation in the orientation of the borehole. Accurate information regarding the spatial position of the instrument along the length of the borehole will also be useful for correlating borehole roughness measurements with changes in stratigraphy, geologic structure, and influx of groundwater.

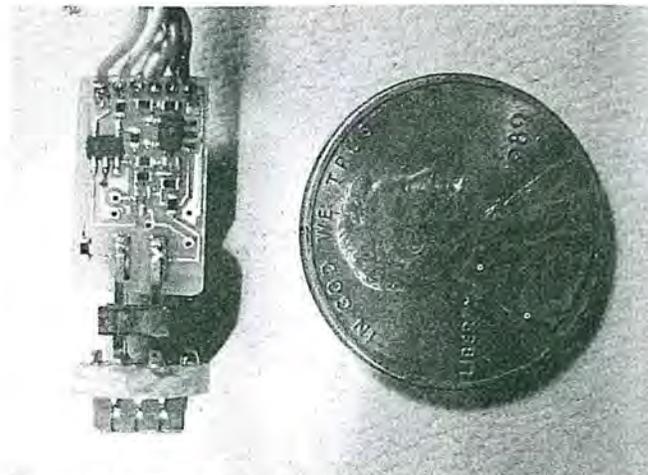


Figure 9. Custom-built tilt meters to be included in new profilometer prototype.

### ELECTRONICS AND DATA ACQUISITION

During development of these prototype instruments, several different data acquisition systems were used to monitor the instrument sensors. Various settings were tested to try to obtain consistent data, and a field data acquisition system was developed for use underground. The brake-hone profilometer strain gauges were monitored during lab tests with an LDS Nicolet Genesis data acquisition system and laptop computer. This system provided many options for changing the monitoring rate and experimenting with filtering as a means of reducing noise. For borehole profiling tests, the strain-gauge sensors were monitored at 2000 Hz, with a Bessel filter and low-pass cutoff frequency of 20 Hz.

A field data acquisition system for the brake-hone profilometer was assembled and used underground. Based on the monitoring parameters identified with the Genesis system, this data acquisition system was composed of three custom circuits, one for each strain gauge sensor, connected to a National Instruments NI-6009 USB digitizer. Data from the digitizer was stored on a laptop running National Instruments Lab View software. Each custom circuit contained an adjustable gain instrumentation amplifier and an adjustable cutoff frequency Bessel filter. The sample rate was set at 2000 Hz with a filter corner frequency of 25 Hz.

The data acquisition system for the potentiometer instrument was based on the National Instruments NI-6009 digitizer. The front-end circuit was composed of a single ended amplifier with all filtering performed in the software. The sample rate was set at 2000 Hz.

A custom data acquisition system is currently being developed for the newest prototype. It uses a position-based digitizer rather than the time-based digitizer that was used in previous models. The three strain gauges interface with independent analog-to-digital converters running at a fixed 10,000 Hz. The dual-axis tilt meter interfaces with an additional analog-to-digital converter. Readings from the strain gauges and tilt meters are stored simultaneously for each channel when a trigger pulse is detected from the optical encoder. Thus, a data file will be automatically produced that lists borehole radii versus the location and orientation of the instrument in the borehole for each scan of the data acquisition system.

# 26th International Conference on Ground Control in Mining

## PROOF OF CONCEPT

Three series of tests were conducted with the prototype profilometer fabricated from brake hone parts to prove the concept of dynamic profiling. A series of sensitivity tests were performed to establish whether the instrument sensors could produce signals that were reflective of surface roughness ranging from medium to smooth. Known-profile and pipe tests were conducted to determine whether the instrument could provide profile signals that accurately represent known borehole profiles.

### Sensitivity Test

A practical test was designed to determine whether the instrument could identify slight changes in surface roughness. Four strips of sandpaper with grits of 50, 150, 320, and LT4 (coarsest to smoothest) and lengths of 7.6, 15.2, 22.9, and 30.5 cm (3, 6, 9, and 12 in), respectively, were laid on top of each other with one end aligned and clamped on a mill table. One of the strain-gauged spring arms of the profilometer was then clamped to the spindle of the milling machine so that the wheel of the profilometer arm would first contact the 50-grit paper, and then drop down in elevation to the 150-grit paper, etc., until the wheel of the spring arm eventually contacted and rolled along the surface of the mill table for the last 7.6 cm (3 in). The mill table was used to move the clamped stack of sandpaper beneath the profilometer arm and thus enable the strain-gauged spring to measure changes in roughness and elevation along the entire 38-cm (15-in) length of the testing surface. The travel speed of the mill table was varied to identify appropriate parameter settings for borehole roughness tests and the sampling rate of the data acquisition system. Each sensor arm of the wheeled profilometer and the stylus profilometer were tested in this manner (figure 10). Although the strain-gauge readings from the stylus profilometer were more representative of the tested surfaces, some residual noise was apparent in all of the tests, indicating that the instrument had difficulty measuring the roughness of smooth surfaces, such as the finely finished surface of the mill table.

### Known-Profile Test

To obtain a test profile of an actual borehole, a section of a jackleg-drilled borehole near a corner of the regular-mix concrete block was cut and removed. A piece of concrete containing about

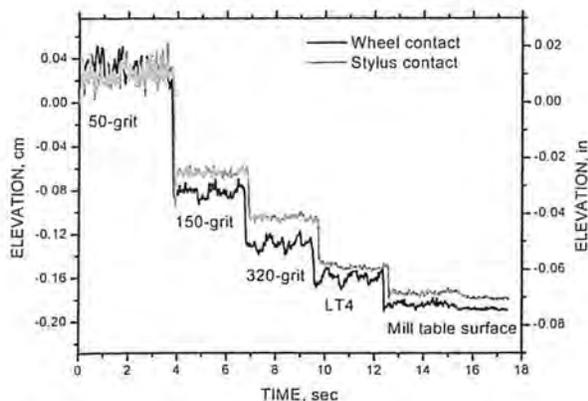


Figure 10. Elevation versus time as measured with one arm of wheel and stylus profilometers. Average horizontal velocity was about 2.1 cm/sec (0.84 in/sec).

one quarter of the borehole was then clamped to the table of a milling machine. A dial gauge accurate to the nearest 0.00254 mm (0.0001 in) was used to manually measure the profile of the borehole's surface every 0.254 mm (0.01 in) along the 43-cm- (17-in-) length of the hole. The prototype profilometer was attached to the spindle of the milling machine, and the mill table was raised until the instrument's spring arm was depressed approximately the same amount as it would be in a 3-1/2-cm- (1-3/8-in-) diameter borehole. As mentioned above, the mill table was then moved beneath the profilometer to allow the strain-gauged arm to measure changes in profile along the entire length of the borehole (figure 11). The typical test results for a strain-gauged spring arm of the wheel and stylus profilometers were compared with the known profile of the borehole, which was measured manually with a dial indicator (figure 12). As the strain-gauged arm of the stylus profilometer was moved along the borehole, friction between the ball bearing mounted on the end of the sensor arm and the concrete surface caused increased vibrations in the instrument, which in turn, led to significant overestimation of many of the peaks and valleys along the profile of the borehole. As the wheel profilometer traveled over the surface asperities, less extraneous pulling force was exerted in its spring arm than in the spring arm of the stylus profilometer. As a result, the wheel profilometer tended to overestimate the peaks and valleys to a lesser degree than the stylus profilometer. However, the wheel profilometer underestimated some of the valleys, particularly if the size of the wheel was large in comparison to the width of the valley. With both types of profilometers, sizeable errors occurred if the sensor arm was pulled sharply or jerked over the peak of an asperity. Conversely, errors also occurred if the sensor arm was dropped suddenly or bounced into a valley after traversing an asperity. In both situations, significant vibration was mechanically induced within the sensor arm, thus producing erroneous readings. Because the wheel profilometer has less frictional resistance than the stylus profilometer, less vibration is induced in the sensor arm as a consequence of the pulling or extraction force. As a result, there is less fluctuation in the instrument's readings. The ball-bearing-tipped arm of the stylus profilometer produced much larger fluctuations in the instrument's readings; therefore, this prototype design was eliminated from further consideration.

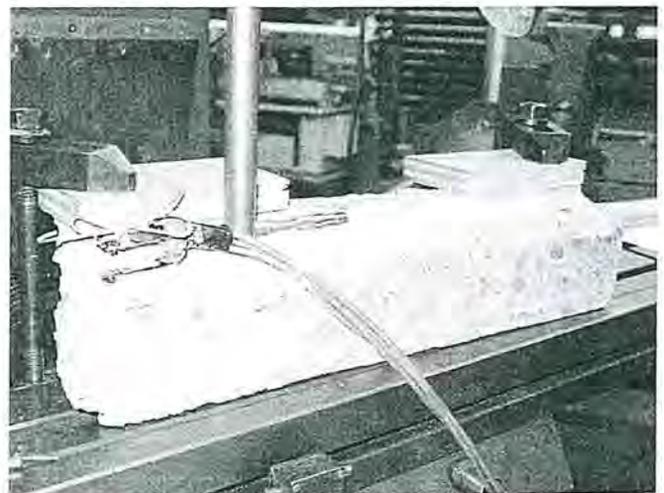


Figure 11. Strain-gauged spring arm of a wheel profilometer being drawn along a section of a borehole cut from a concrete block.

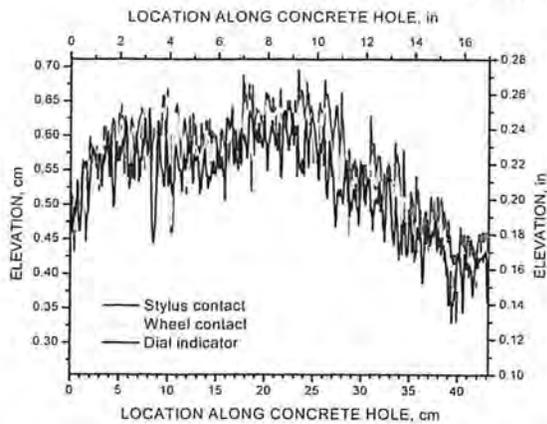


Figure 12. Comparison of elevation versus location along a section of a concrete hole as measured with the wheel and stylus profilometers, as well as with a manual dial gauge.

**Pipe Test**

A pipe test was conducted to evaluate the instrument's performance measuring a known profile in a borehole-like setting. A pipe-test apparatus was constructed to simulate a borehole having known changes in diameter at specific locations along its length. A short section of steel pipe, approximately 3-1/2 cm (1-3/8 in) in diameter, was cut into three pieces, each about 28 to 30.5 cm (11 to 12 in) in length. Mating ends of the pipe sections were machined in a lathe to form a slip joint. The inside diameter of one end of pipe was enlarged, and the outside diameter of the mating end of the opposing pipe section was reduced so that the two sections of pipe could be joined together in a slip joint. However, the female end of the pipe was machined for a longer distance along the inside length of the pipe so that an interior groove was formed at each joint when the pipe sections were pressed together. After the sections of pipe were joined together, the joints were reinforced with duct tape, and the entire column was mounted vertically to the leg of a work table. Various experiments were conducted with the prototype profilometers in the pipe-test apparatus to develop a driver mechanism for the instrument, identify appropriate extraction speeds, and assess the relative position of the instrument as it was moved through the pipe sections.

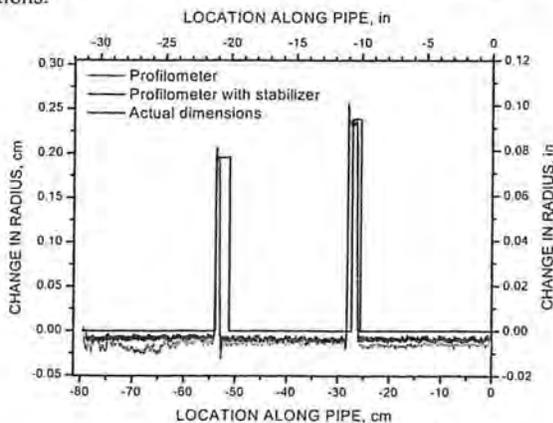


Figure 13. Change in radius versus location along pipe as measured with wheel profilometer. Actual dimensions are also shown.

Based on these experiments, a constant-velocity driver was developed for pulling or extracting the profilometer from the pipe (figure 6). After clamping the device to the table so that its extraction rod was aligned with the axis of the pipe, a series of tests were conducted with the wheeled profilometer over the entire length of the pipe-test apparatus. The changes in radius measured by the profilometer during these tests were compared to the actual profile of the pipe's radius, which was measured manually with a vernier and a tape measure (figure 13). From these tests, it was evident that mechanical vibration of the constant-velocity pulling apparatus was contributing noise to the signals collected from the instrument's sensors. To minimize this vibration, the driver belt pulleys were realigned, and a borehole stabilizer was added to the stem of the instrument (figure 7). These measures noticeably reduced the amplitude of the signal noise caused by mechanical vibration.

Pipe tests were also conducted with the potentiometer profilometer with the wheeled levers. Because accurate information regarding the location of the radial measurements for the levered-arm profilometer could not be obtained, the results of both the brake-hone and the levered-arm profilometers were plotted with time (figure 14). For the levered profilometer, the actual time to complete the test was over 105 sec, but this time was compressed so that it corresponded to the maximum test time of the wheeled, brake-hone profilometer. For the actual profile, time was manufactured linearly according to location. The amplitudes of change in radius measured by both instruments reasonably match the actual radial profile of the pipe. Results of the levered profilometer show offsets that may be caused by tilting of the instrument body. The shift in time for the location of the machined pipe grooves as determined with the levered profilometer is a result of nonuniform velocity when pulling the instrument out of the pipe by hand.

**Summary**

Although the stylus profilometer with the ball-bearing contacts was more sensitive to smoother surfaces, its performance with rougher surfaces was poor. The wheeled profilometer was best able to represent a potentially rough surface profile, and the stabilizer helped minimize mechanical vibration. The levered profilometer produced reasonable results, but the user must develop a technique to maintain a near-constant pulling velocity so that the radius of the borehole is sampled as uniformly as possible.

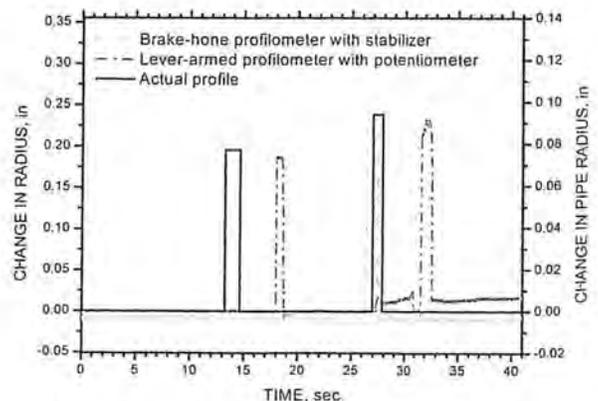


Figure 14. Change in radius of pipe versus time. Time coordinates of levered profilometer and actual profile were calculated or adjusted to match time of profilometer with stabilizer.

### Field Troubleshooting

The wheeled, brake-hone profilometer was taken to a coal mine to troubleshoot its operation in 2.4-m (8-ft) long boreholes. In spite of its adjustment capability, the constant-velocity driver was difficult to correctly position at the collar of the borehole and to anchor to the mine roof so that its extraction rod was aligned with the centerline of the borehole. Mounting the driver mechanism to the mine roof was cumbersome and, ultimately, undesirable. Because the driver belt tended to slip and stall, the location of the instrument within the borehole could not be accurately tracked. For these reasons, a much more practical instrument was designed for use underground. This experience has led to a parallel research approach whereby a simple, robust profilometer (the levered profilometer) was developed for efficiently collecting borehole roughness measurements in the field, and a more sophisticated, scientific instrument (described earlier as the final prototype) will be developed for obtaining accurate, repeatable test results, analyzing the relationship between roughness parameters, and investigating the influence of geologic factors.

### METHODS OF REPRESENTING SURFACE ROUGHNESS

Several methods are available to represent surface roughness in numerical form, depending on the type of measurements that are collected. A couple of methods of representing surface roughness are presented here with their mathematical representations so that the reader can clearly tell the difference between them.

Myers (17) proposed a roughness parameter,  $Z2$ , which is the root mean square of the first derivative of the profile. That is,

$$Z2 = \left[ \frac{1}{L} \int_0^L \left( \frac{dy}{dx} \right)^2 dx \right]^{\frac{1}{2}}, \quad (1)$$

where  $L$  is the length of the sampling plane,  $dy$  are changes normal to the sampling plane, and  $dx$  are increments along the sampling plane.

$Z2$  can be rewritten in summation form as

$$Z2 = \left[ \frac{1}{L} \sum_{i=1}^n \frac{(y_{i+1} - y_i)^2}{(x_{i+1} - x_i)} \right]^{\frac{1}{2}}, \quad (2)$$

where  $n$  is the number of sampling intervals.

Tse and Cruden (18) digitized 10 standard profiles and found a relationship between  $Z2$  and the joint roughness coefficient (JRC) proposed by Barton and Choubey (19). The relationship is

$$JRC = 32.2 + 32.47 \log(Z2). \quad (3)$$

$Z2$  showed the best and most consistent correlation to JRC than any other independent parameter (18). Where spatial relationships are obtained along the sampling plane,  $Z2$  will be used to assess surface roughness. In practical terms, the profilometer data will be analyzed using the  $Z2$  roughness parameter when accurate

information is collected for the following parameters: the overall length along the borehole axis in which roughness measurements are collected ( $L$ ), measurements of borehole radius ( $y$ ), and the location along the length of the borehole for each individual radius measurement ( $x$ ).

Because data from the levered profilometer does not include specific information regarding the location of the average borehole radius measurements, the spatial relationship of the data along the sampling plane is not available. Therefore, a different measure of roughness is needed for this instrument. The average increment between samples in the direction normal to the sampling plane is tentatively proposed for this case, or

$$Ave\ incr = \frac{1}{n} \sum_{i=1}^n |y_{i+1} - y_i|. \quad (4)$$

Further tests are needed to compare the average increment with  $Z2$  and to determine whether either of these roughness parameters are related to the anchorage capacity of a borehole.

### BOREHOLE PROFILING RESULTS

Borehole profile tests were conducted in the concrete blocks with both the wheeled, brake-hone profilometer and the wheeled, lever-arm profilometer. Measured profiles typically showed distinct differences between the smooth holes drilled with the diamond bit and the rougher holes drilled with the tungsten-carbide and jackleg bits (figure 15). Multiple runs or repeated tests with the same instrument in a borehole were generally consistent as long as the orientation of the instrument and the profiling track were kept constant. However, variations in the measured profiles are likely explained by slight changes in the profiling track and occasional changes in the orientation of the instrument which were observed to occur between runs during these tests. Because of the possible variations induced by non-constant orientations during these tests, some of the profile measurements may need to be repeated under more controlled conditions to improve the accuracy of the test results.

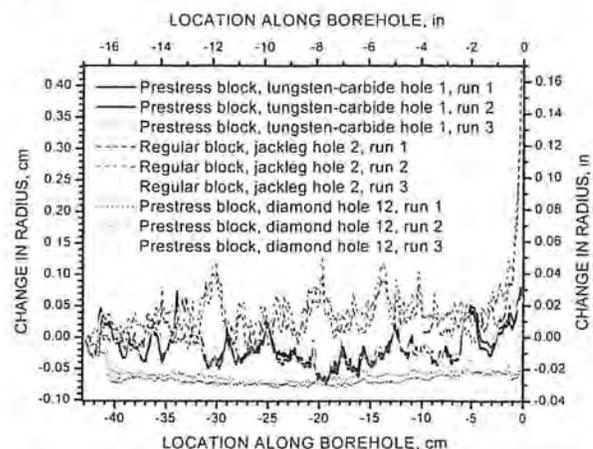


Figure 15. Change in radius versus location along borehole for two boreholes in concrete, as measured with wheeled profilometer without a stabilizer.

## 26th International Conference on Ground Control in Mining

Excluding measurements from the first and last 1.27 cm (1/2 in) of the tests, Z2 values were calculated for profiles measured with the wheeled, brake-hone profilometer. Average changes in radii between scans were calculated for the radii measured with the levered profilometer over approximately the same lengths in these holes. However, none of the holes drilled with the tungsten-carbide bit in the regular-mix concrete block were profiled with the brake-hone profilometer. A comparison of the Z2 values and the average increment of radii show that these two roughness parameters are probably related (figure 16). If two outlying data points representing jackleg holes in the prestress block are excluded, a linear relationship can be fitted, having a correlation coefficient,  $r^2$ , of 0.577. Further profiling and SEPT tests are needed to establish the relationship between these parameters and determine whether they are related to resin roof bolt anchorage strength.

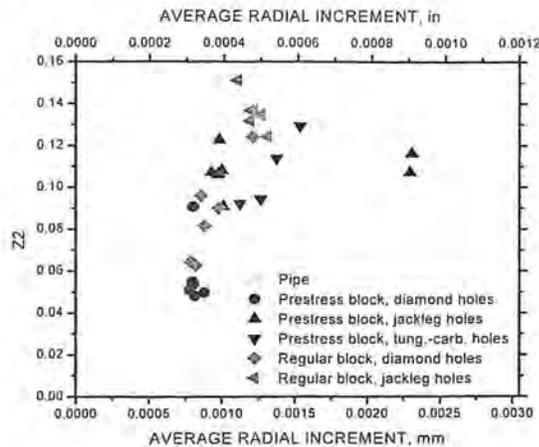


Figure 16. Z2 versus average radial increment in boreholes drilled in two concrete blocks.

### INITIAL SHORT ENCAPSULATION PULL TESTS

Several #7 bolts were installed in test holes in both concrete blocks (figure 1), first using a fast-setting resin (Minova Lokset<sup>1</sup> resin 3212 LIF 35 cartridges) and later with a slower-setting resin (3212 H90 cartridges) to achieve better mixing of the resin components. The bolts were installed using an impact wrench with a rotation speed which typically varied from 150 rpm at the start to 300 rpm at the end of the installation procedure. With the fast-setting resin, the bolt was usually seated in about 3 seconds and spun for an additional 7 seconds as recommended by manufacturer. With the slow-setting resin, the bolt was normally seated in about 6 seconds and then spun for an additional 15 seconds.

SEPTs were conducted with all of these bolts to determine their anchorage capacity. In all of these tests, failure unfortunately occurred at the resin-bolt interface rather than the resin-concrete interface. Maximum load ranged from 142 to 249 kN (32 to 56 kip), sometimes well above the bolt's yield point of 160 kN (36 kip). To avoid exceeding the yield strength of the bolt, two additional bolts were installed with half a cartridge of the slow-setting resin. However, during subsequent pull tests with these bolts, failure still occurred at the resin-bolt interface.

<sup>1</sup> Mention of specific products does not imply endorsement by NIOSH.

These results are surprising, considering that short encapsulation pull tests are specifically designed to induce failure at the interface between the resin and the medium in which the bolt is installed. In similar tests conducted by Pettibone (2), the majority of the reported failures appear to have occurred at the resin-concrete interface. Further tests may therefore be needed with additional bolts installed in the two concrete blocks to confirm these initial results and if necessary, to modify the test procedures so that valid conclusions regarding anchorage strength can be obtained.

Although the anchorage capacity of the boreholes could not be quantified by these initial SEPTs, the results do indicate that the resin bolts had more than adequate anchorage strength. The limiting factor during these tests was the bond strength at the resin-bolt interface rather than the strength of the resin-concrete interface. Unfortunately, the results of these initial tests are inconclusive in terms of the profilometer research because a direct relationship can not be established between either the roughness of the boreholes (drilled with diamond, tungsten-carbide, and jackleg bits) or the strength of the medium (prestress-mix and regular-mix concrete) and the maximum loads that were measured during the pull tests. Further laboratory tests will have to be conducted in a weaker medium to successfully correlate borehole roughness with anchorage capacity before evaluating the instruments and conducting SEPTs in weak rock in underground coal mines.

### CONCLUSIONS

The concept of dynamically profiling a borehole to determine a numerical measure of surface roughness has been proven in the laboratory. Experiments were conducted with several profilometer designs to develop two prototype instruments that measure changes in a borehole's radius using either strain-gauged, spring-steel arms or rigid, steel arms attached to a spring-loaded cone and a linear potentiometer. In both of these instruments, a small wheel is used to contact the surface of the borehole rather than a stylus to reduce the amount of mechanical vibration and extraneous force induced within the instrument by surface asperities in the borehole's wall. Roughness profile tests were conducted with both instruments in boreholes drilled in two concrete blocks using three different drilling techniques. Both instruments were able to consistently distinguish the difference between smooth holes drilled with a diamond bit and rougher holes drilled with a tungsten-carbide bit or a jackleg bit. Profiling results were repeatable when the instrument was oriented consistently and the same profile was tracked along the length of the borehole during multiple runs of a test. Data collected from the two profilometers during the borehole profile tests were analyzed in terms of a Z2 roughness parameter and an average radial increment. These two numerical measures of surface roughness appear to be linearly related as defined by a correlation coefficient ( $r^2$ ) of 0.577. Short encapsulation pull tests were conducted with resin bolts installed in the two concrete blocks, but all of the pull tests failed at the resin-bolt interface rather than the resin-concrete interface. As a result, further research is needed to properly correlate borehole surface roughness and the strength properties of the host medium with borehole anchorage capacity.

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## 26th International Conference on Ground Control in Mining

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